

# **A QUANTITATIVE APPROACH TO MILITARY WATER SYSTEM VULNERABILITY ASSESSMENTS**

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## **Abstract**

The Department of the Army routinely conducts water system vulnerability assessment (WSVA) on military water distribution systems (WDS). Risk assessors construct attack scenarios and then estimate the risks using their expert judgment. These risk assessments are traditionally difficult to support with evidence and historical data. As a result, decision makers often question the validity of the assessor findings and their recommendations. The goal of this research paper is to improve the WSVA program by presenting decision makers with quantifiable risk. I propose a hybrid risk analysis based on hydraulic modeling and probabilistic risk analysis. This improved methodology (WSVA2) presents a quantitative approach to risk assessment and uses simulations to support the assessor's expert judgment. A fictitious military WDS and its data are created to avoid disclosure of sensitive information. Hydraulic simulation models are used to assess the consequences of a successful contamination attack and to evaluate the outcome of a catastrophic scenario. Three unknowns of the scenarios are the contaminant toxicity, contaminant reaction rate in water and contaminant quantity used in the attack. Attack simulations are randomly generated using distribution curves based on both known studies and assumptions. Monte Carlo simulations are used to quantify the uncertainties of the model. Findings show that 53,126 Exposure Incidents (EI) resulted from the contamination attack on Water Tower 1. In the catastrophic scenario, over 400,000 EI occurred in 1 week which affected over 4,000 people in the Hexagon Building. And in an attack-response scenario, hydraulic modeling is used to demonstrate that the current Emergency Response Plan (ERP) cannot sufficiently mitigate the contamination threat below Military Exposure Guideline (MEG) level.

Advisor: Dr. Seth Guikema

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## Table of Contents

Abstract .....	ii
Acknowledgements.....	iii
List of Tables .....	vi
List of Symbols, Notation, and Definition.....	vii
List of Figures.....	viii
1. Introduction .....	1
1.1 Assessor bias and intuitive risk judgments .....	2
1.2 WSVA2 Improvements .....	3
2. Literature Review .....	4
2.1 Water System Vulnerability Assessments .....	4
2.2 Infrastructure Interdependency.....	5
2.3 Blue Zone (Virtual City).....	5
2.4 Hydraulic modeling .....	7
2.5 Agent Based Modeling.....	8
2.6 Value Trees .....	8
2.7 Contaminant Exposure .....	9
3. Analysis and Results .....	11
3.1 Risk Classification .....	11
3.1.1 Threat determination .....	12
3.1.2 Consequence determination and Multi Attribute Utility Theory (MAUT) .....	13
3.1.3 Vulnerability determination.....	15
3.2 Quantification of Risk .....	16
3.3 Simulation .....	17
3.4 Uncertainties in model inputs.....	18
3.5 Evaluation of a Catastrophic Scenario .....	22
3.6 Sensitivity Analysis .....	24
3.7 Emergency Response Plan Evaluation .....	28
4. Conclusions and Future Work.....	32
4.1 Conclusions .....	32
4.2 Future Work .....	32
Reference .....	34

Resume..... 37

## List of Tables

Table 1. Threat Scores .....	13
Table 2. Disutility for Contamination .....	14
Table 3. Constructed Scale for Vulnerability .....	16
Table 4. Risk Table.....	17
Table 5. Uncertainty Distribution.....	19

## **List of Symbols, Notation, and Definition**

### **Abbreviation Key**

ABM	Agent Based Modeling
DOD	Department of Defense
DPW	Department of Public Works
EPA	Environmental Protection Agency
ERP	Emergency Response Plan
MAUT	Multi- Attribute Utility Theory
MCL	Maximum Contaminant Level
MEG	Military Exposure Guideline
US	United States
USAPHC	United States Army Public Health Command
WDS	Water Distribution System
WSVA	Water System Vulnerability Assessment
WSVA2	Hydraulic Model Based Risk Analysis

## List of Figures

Figure 1. WSVA Methodology and WSVA2 Additions .....	4
Figure 2. Blue Zone .....	7
Figure 3. Value Tree for Terrorism Consequences.....	9
Figure 4. Global Terrorist Attack Map 2012 .....	13
Figure 5. Histogram for 2500 Simulations .....	21
Figure 6. Time Series Exposure from MC Simulations .....	21
Figure 7. Contaminant Propagation.....	24
Figure 8. Sensitivity Analysis of (a) MEG Sensitivity, (b) Contaminant Reaction Rate Sensitivity, (c) Quantity Sensitivity. ....	27
Figure 9. Flushing Nodes .....	29
Figure 10. Flushing Effectiveness.....	30
Figure 11. Mitigation Comparison Analysis .....	31



# **1. Introduction**

The Bioterrorism Response Act of 2002 required the Department of the Army to routinely conduct water system vulnerability assessments (WSVA) on United States (U.S.) military water distribution systems (WDS). A standard qualitative risk analysis adapted from various Federal agencies is the current methodology used to conduct the WSVA. Physical destruction, contamination, and cyber attacks on the WDS are the three focuses of the assessment.

In the past, Army assessment teams traveled to various military installations to conduct the WSVA and present their risk findings and recommendations to the installation commander (decision maker). The risk evaluation process is based on the first three steps of the Army Risk management process. Each WSVA team is responsible for identifying and assessing hazards, estimating probability and severity, and assigning a risk category (e.g. High, Medium or Low Risk) for each scenario (USACHPPM TG 188, 2008). Unfortunately, the risk presented in each assessment is inconsistent because it is based on expert judgment and loosely defined guidelines. Furthermore, the results are not strongly supported by relevant data. Decision makers have openly questioned the effectiveness of the WSVA and their recommendations, and some unnecessary and costly countermeasures could result if assessor recommendations were implemented at military facilities.

This research paper aims to improve the current WSVA with the use of hydraulic modeling verification. EPANet 2.0 (hydraulic simulation software) is used to model the transport of contaminants throughout a military WDS in order to evaluate attack scenarios and mitigation methods. In addition, probabilistic risk analysis based on the hydraulic modeling results is used to quantify the risks. The new methodology is a hydraulically-informed risk analysis referred to

as WSVA2. The Department of Defense (DOD) could substitute actual data into the WSVA2 model and make it a realistic risk assessment tool for military WDS.

## **1.1 Assessor bias and intuitive risk judgments**

There are several factors which will lead to assessor bias in the current WSVA. First, members of the assessment teams are not risk experts with extensive analytical training. Generally speaking, WSVA risk assessors rely on their intuitive judgments. Like most Americans, the assessors have risk perceptions based on their individual knowledge and experience.

Unfortunately, the dominant perception for most Americans is one that contrasts sharply with the views of professional risk assessors. The untrained risk assessor believes that “they face more risk today than in the past and that future risks will be even greater than today’s” (Slovic, 1987).

Second, data is not easily obtainable in regards to military infrastructure vulnerability.

Incomplete or irrelevant data in reference to attacks on water systems could likely be misinterpreted by the assessors. If the relevant data was available, statistical analysis may be able to help improve the understanding of potential threats than current WSVA methods of analysis, though how well such data would represent future threat scenarios would need to be determined.

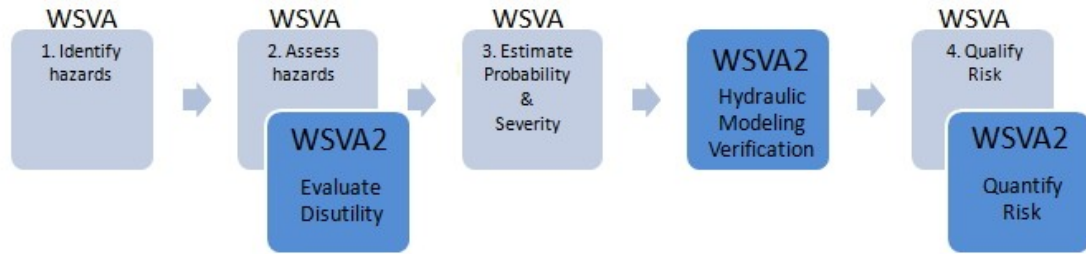
Third, personal expertise influences every WSVA. Probability assessments reflect expert knowledge as intended, but it also influences the individual risk assessor conducting the assessment (Guikema and Aven, 2011). Simply stated, all assessors have bias and they don’t know that they have bias. However, if they recognize their own bias, they can use it to improve their assessment. Often, an assessor with an engineering background may offer different assessments of probability and consequences of contamination than an assessor with an

environmental health background. Their assessments will likely lead to disagreements using the same risk methodology.

Lastly, the risk assessment results are ambiguous in nature and will fail the Clarity Test. A decision maker may ask, “What is the risk of contamination to my WDS?” And the assessor cannot answer the decision maker with specific time periods, contamination exposure incidents, how much of the WDS is at risk, and so on. In the current WSVA methodology, the presented results may lead to ambiguity and miscommunication on the nature of the risk.

## **1.2 WSVA2 Improvements**

The WSVA2 methodology incorporates hydraulic modeling and probabilistic risk analysis to improve the strength of the WSVA. Three steps are added to the original methodology (Figure 1). First, when assessing hazards (WSVA step 2), qualitative threat and vulnerability assessments are converted into quantitative scores. The assessor will use Multi Attribute Utility Theory (MAUT) to assess the decision maker's disutility (preference) in regards to consequences. The second addition is to use hydraulic modeling to estimate the consequences of the considered scenarios. If assessors speculate that a specific attack scenario has a high consequence, hydraulic modeling results can support or refute the assessors' claim. Lastly, changing the risk classification from a qualitative to a quantitative scale will assist decision makers in understanding the relative nature of risk and in making better-informed decisions.



**Figure 1. WSVa Methodology and WSVa2 Additions**

## **2. Literature Review**

### **2.1 Water System Vulnerability Assessments**

Army guideline states that current procedures and safeguards are adequate to prevent unintentional contamination of water operations and possibly alert the installation to acts of terrorism. However, it also states that with relatively little effort, terrorists can assault the WDS and cause catastrophic effects (USACHPPM TG 188, 2008). Currently, most military WDS are managed by civilian contractors. Whether current safeguards are enough to quickly detect water contamination is questionable. In 2013, the American Society of Civil Engineers reported that America's water infrastructure earned an overall grade of D. In addition, an estimated \$1 trillion is required over the next 25 years for the most urgent pipe replacements (American Society of Civil Engineers, 2013). Given the generally poor state of water system infrastructure in the U.S., it is unlikely that current safeguards are enough to deter a determined attack on the military WDS, despite its secure location. Presumably, a successful attack on the WDS can occur given current realities. Therefore, WSVa2 will also need to seriously evaluate the effectiveness of the installation's Emergency Response Plan (ERP).

## **2.2 Infrastructure Interdependency**

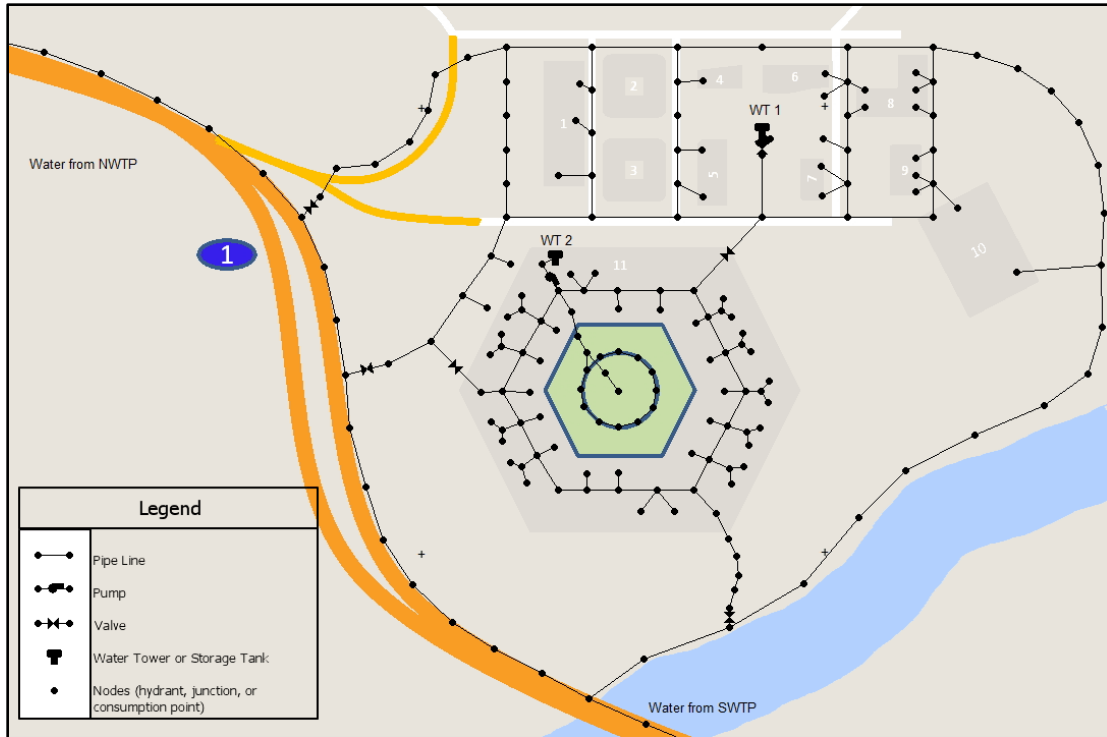
The WDS is a critical infrastructure (CI) integrated into many aspects of daily military operations. Often, decision makers take the WDS for granted not understanding the interdependencies between it and other military infrastructures. An attack on one CI may cause a cascading effect onto other infrastructures, ultimately degrading military readiness. One unique aspect of military installations is that they contain significant amounts of technological computer and communication equipment essential for the modern combat environment. These sensitive equipments require environmental control systems that are dependent on water to function properly. Without a constant water supply to the building, environmental control systems will eventually shut down and cause the indoor temperature to rise rapidly. As a precaution, the sensitive computer equipment may self shutdown much sooner to prevent overheating. The rate of failure increases as modern infrastructures become more advanced and interdependent on CI (Macaulay, 2009). An attack on the WDS may cause unforeseeable secondary and tertiary effects on military operations. Therefore, risk assessors must recognize the rippling effect of CI failure and discuss these risks with decision makers.

## **2.3 Blue Zone (Virtual City)**

WDS websites and Google Maps <sup>TM</sup> contain information that can potentially be exploited by individuals or groups with malicious intent. In order to protect sensitive information, a virtual military district and its WDS was created based on the foundations of Micropolis (Brumbelow et al., 2007). This research created Blue Zone, which mimics a American military district in a hostile country but is entirely fictitious. CI details are built into Blue Zone to better assess the consequences of water disruption. Many of Blue Zone's hydraulic characteristics are imported from Micropolis to simulate a realistic WDS. The Blue Zone contains a collection of various

foreign and American government buildings which employs 10,000 people. The main building of focus, the Hexagon building, employs 6,900 American service members, defense contractors, and diplomats during the day time. The zone's 11 primary buildings, roads, and hydraulic network are shown in Figure 2. Blue Zone's WDS is comprised of a network of 211 pipes built in the 1950s. The U.S. military made additional improvements to the WDS in 2013 but the overall distribution is still in poor quality due to a lack of maintenance of many years. Due to its strategic importance, sophisticated water quality monitors were installed in the Hexagon building to detect water quality degradation. A single 2.20 million gallon (8,339,996 liter) elevated water tower (Water Tower 1) is located in northern section. A 1.65 million gallon (6,254,997 liter) water tank (Water Tank 2) is located within the Hexagon building to serve as a backup.

Two local Water Treatment Plants located north and south outside of the area displayed in Figure 2 supply Blue Zone with potable water. The WDS is specified down to individual service connections for the majority of Blue Zone. The Hexagon building has a higher resolution of water connections to better demonstrate the contaminant transport effects using EPANet 2.0. In order to mimic the chaotic infrastructure of the host country, the WDS was built in a manner that is functional but not in accordance with first world infrastructure codes. The hydraulic model includes 198 nodes, 6 valves, 4 pumps, 2 reservoirs and 2 tanks. The WDS demand nodes are composed of 11 institutional and 1 commercial user (Hexagon Café). Commercial and institutional water demands were based on the research by Haestad (Haestad et al., 2003). The total daily demand of the WDS is 5.58 MGD with minimum and maximum hourly demands of 32,328 gallons and 472,050 gallons, respectively.



**Figure 2. Blue Zone**

## 2.4 Hydraulic modeling

Hydraulic and contaminant fate and transport modeling can be used to verify scenarios that the assessor considers high impact. This paper will demonstrate the use of hydraulic modeling on only one scenario. Unless significant resources are available, it is simply not feasible to model every conceivable scenario. The hydraulic models for this research paper are based on the techniques from Torres et al. (2009). Torres demonstrated EPANet 2.0's hydraulic, contaminant fate and transport modeling potential on the virtual city of Micropolis. The two governing equations of fluid mechanics used in EPANet are the conservation of mass (continuity) equation and conservation of energy (Rossman, 2000).

Contaminant decay is modeled as a first-order reaction in EPANET:

$$\ln\left(\frac{c}{c_0}\right) = -kt$$

$c$  is the contaminant concentration at time  $t$ ,  $c_0$  is the initial contaminant concentration,  $k$  is the growth /  $(-k)$  decay constant, and  $t$  is the time elapsed since the introduction of contaminant into the system (Torres et al., 2009).

Torres et al. also demonstrated the use of Monte Carlo simulations in Visual Basic to quantify outcome uncertainties. To build on Torres' work, this paper used MATLAB R2013a in conjunction with EPANet Toolkit to run iterative hydraulic simulations.

## 2.5 Agent Based Modeling

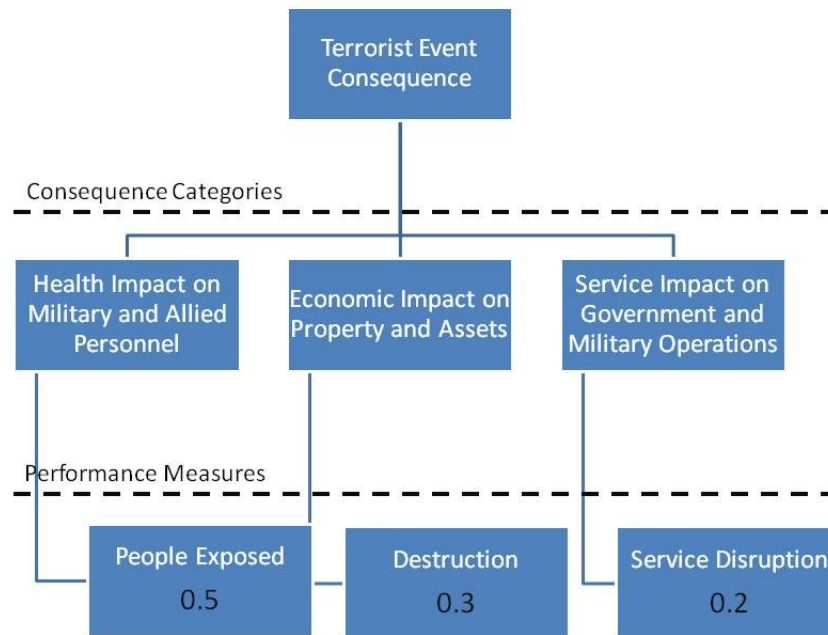
In a contamination event, consumers collectively influence the hydraulic state of the WDS which will affect the number of people exposed to the contaminant. Each consumer has a set of behavior such as mobility, ingestion of tap water, changes in water usage and notifying other people. Zechman (2011) used Agent Based Modeling (ABM) to demonstrate the interactions among consumers based on word-of mouth communication. This paper did not use a sophisticated model as such ABM to predict consumer water demand decrease. However, it did use a simplistic non-linear method to account for consumer compliance after the public announcement is issued by the military.

## 2.6 Value Trees

Apostolakis and Lemon (2005) developed a value tree for the prioritization of MIT infrastructure for security protection to represent the values of its various stakeholders. For simplicity, I use the MIT value tree to represent preferences in this work. In practice, this value tree would need to be



reassessed in light of the likely differences in preferences between an open, urban campus and a secure military facility. This reassessment was beyond the scope of the present work. The final value tree of an attack on the WDS is shown in Figure 3. The weights (performance measures) may vary for each military installation due to the different adverse impacts the attack may have on operations.



**Figure 3. Value Tree for Terrorism Consequences**

## 2.7 Contaminant Exposure

In Epidemiology, exposure is defined as “a state of contact or close proximity to a chemical...by ingesting, breathing, or direct contact (<http://medical-dictionary.thefreedictionary.com/exposure>).” Common forms of exposure to water contaminant are by ingestion or skin exposure. Water vapor inhalation is also possible but the effects are assumed negligible here because this work is focused on acute effects and vapor inhalation from

potable water is typically of concern for more chronic health effects. In the hydraulic model, exposure occurs when a person consumes water from a contaminated node. Each time this occurs, it is recorded as an exposure incident (EI). If a person received multiple EI in a short amount of time, it would significantly increase their health risk and cause substantial concern. There may be a variety of naturally occurring contaminants in the WDS, but decision makers should only concern themselves with contaminant concentrations above the military exposure guidelines (MEG). MEGs are similar to the EPA's Maximum Contaminant Level (MCL), which are guidelines to evaluate the significance of contaminant exposure. In some instances, MEG levels are slightly higher than MCL because all consumers are assumed older than the military age of 18 in the Blue Zone.

Usually, decision makers would like to know the worst case scenario of a contamination event. However, both high level and low level exposures are concerns which could lead to adverse outcomes. High-level exposures could result in immediate health effects and/or significant impacts to mission capabilities. Low-level exposures may result in delayed and / or long-term health effects that would not ordinarily have a significant immediate impact (USACHPPM TG 188, 2008). Realistically, the worst case scenario is rarely known, but there are many lower levels of adverse health impacts less severe than the worst case scenario. Any casualty estimates would likely be grossly inaccurate due to the type of hazard, sources of exposure, contaminant concentration, contaminant toxicity, frequency, duration of exposure, and natural human variability in susceptibility to the contaminant. In order for a contamination attack on the WDS to be effective, the contaminant(s) used must be highly toxic. This paper assumes that the exposed population will suffer noticeable adverse effects which will cause immediate and noticeable decrease to operational readiness. Low-level exposures, while still important, are not analyzed in the paper due to the difficulty of estimating health impact over time and the likely lack of feedback to short-term operational readiness.

### 3. Analysis and Results

This section explains the risk associated with an intentional attack on a military WDS. In the example scenario, a contaminant of unknown toxicity and quantity was released in Water Tower 1 at midnight. WSVA2 methodologies are applied to the scenario to evaluate risk. First, the components of risk are explained in detail. Second, the uncertainties of risk are evaluated for their effect on the outcome. Lastly, the outcomes and mitigation strategies are examined in a catastrophic scenario.

#### 3.1 Risk Classification

A change in risk classification is required to quantify risk. In the WSVA methodology, risk is a qualitative function of probability and severity. In WSVA2, risk is determined as:

$$R = f(TCV)$$

R is the overall risk, T is the threat characterized by the installation's likelihood of terrorist attack, C are the consequences measured by the decision maker's disutility, and V is the vulnerabilities assessed by the WSVA team (Torres et al., 2009). Risk is often thought of as  $R = T \times C \times V$ , but this would imply a use of expected values, a conceptualization of risk that has significant problem (e.g., Aven and Guikema, 2014). For the purposes of this work, we will proceed with a

$R = T \times C \times V$  definition but acknowledge that this may be insufficient in some situations. It is, however, a significant advance over current practice.

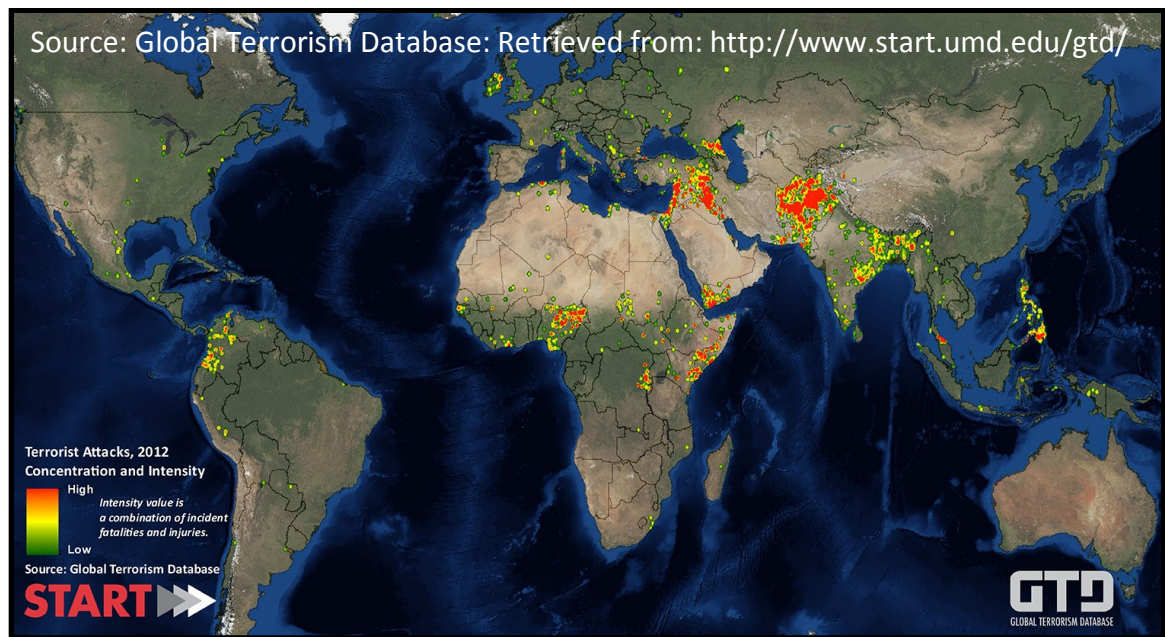
### 3.1.1 Threat determination

The threat component is arguably the most uncertain aspect of security risk because it is difficult to estimate the probabilities of future threats. However, game theorists have shown that terrorists shift their attention toward softer targets in reaction to the security investments made by defenders (McGill et al., 2007). Although military WDS are not prime targets now, hostile groups or individuals may eventually shift their focus to water systems. Terrorist attack occurrences from historical data can provide a starting point for quantifying the threat to the WDS. We suggest here starting from the historic attack frequency data and using a quantitative, but judgment-based scale for assessing threat. The political and geographic location of a particular facility is perhaps the single most important factor that influences this assessment. A score of 0 indicates no threat and a score of 1 indicates certainty of imminent attack. Figure 4 maps known actual terrorist attacks which occurred in 2012. One can see that the terrorism concentration in the Middle East and Central Asia is many times higher than the continental U.S., which in turn reflects the regional threat level.

This paper will not reveal actual threat levels to overseas military installations. Instead, it will compare the relative threat at Blue Zone to five other fictitious U.S. military installations around the world (Table 1). The Threat value used for Blue Zone ( $T = 0.70$ ) is used in a later section to determine the Risk Scores. DOD could substitute real threat data into the WSVA2 model to potentially determine the proper allocation of countermeasure resources.

**Table 1. Threat Scores**

Threat	Installation
0.07	Capital Military District (Washington D.C.)
0.70	Blue Zone (Middle East)
0.68	Camp Patton (Southeast Asia)
0.32	DMZ (Korea)
0.73	Camp Smith (North Africa)
0.01	Jefferson National Labs (U.S.)



**Figure 4. Global Terrorist Attack Map 2012**

### **3.1.2 Consequence determination and Multi Attribute Utility Theory (MAUT)**

Multi-attribute utility theory (MAUT) provides a theoretically strong method for combining preferences across multiple attributes for single decision-makers (Keeney and Raiffa, 1976). The use of MAUT will help to eliminate inconsistent and conflicting preferences representations amongst both decision makers and risk assessors. Each person may determine the consequences of a terrorist attack differently because utility theory is inherently a single-person preference

model. This flexibility in measuring disutility allows each decision maker to judge the importance of their WDS in respect to the installation's military operations. Through a series of interview questions and comparisons based on MAUT, the assessor finds the decision maker's disutility for each of the three possible consequent outcomes of an attack: 1) number of people exposed to a contaminant 2) destruction of WDS component (in dollars), and 3) service disruptions (in number of days without water). Table 2 demonstrates what the decision maker's disutility could look like for the first aspect, the number of people exposed to a contaminant with an example disutility function. All three sets of disutility values are between 0 and 1. A value of 0 is the best possible outcome while a value of 1 is the worst possible outcome. In practice, the disutility function would need to be assessed with the decision-maker for each facility.

**Table 2. Disutility for Contamination**

Disutility	Discription
<b>0</b>	This category represents no consequence for the Hexagon. People may have been exposed to the contaminant but it is under the MEG. The U.S. mission in host country is not affected by the attack.
<b>0.2</b>	This category represents a moderate consequence for the Hexagon. 215 (3.12% - 6.23%) but less than 430 of the people are exposed to the contaminant over the MEG. The U.S. mission in host country is slightly affected by the attack.
<b>0.4</b>	This category represents a moderate consequence for the Hexagon. 430 (6.23% - 12.5%) but less than 862 of the people are exposed to the contaminant over the MEG. The U.S. mission in host country is somewhat affected by the attack.
<b>0.6</b>	This category represents a severe consequence for the Hexagon. 862 (12.5% - 25%) but less than 1725 of the people are exposed to the contaminant over the MEG. The U.S. mission in host country is affected by the attack.
<b>0.8</b>	This category represents an extreme consequence for the Hexagon. 1725 (25% - 50%) but less than 3450 of the people are exposed to the contaminant over the MEG. The U.S. mission in host country is heavily degraded by the attack.
<b>1</b>	This category represents an catastrophic consequence for the Hexagon. 3450 (> 50%) or more people are exposed to the contaminant over the MEG. The U.S. mission in host country cannot function.

The value tree helps the decision maker identify the importance of each attribute of consequence. Critical installation stakeholders can contribute to the weighting of the adverse measures. An example value tree for the Blue Zone is shown in Figure 4. Each installation should evaluate and assign their own relative importance for each consequence based on their unique situation.

The consequence component of risk (C) is calculated using the standard multi-attribute utility calculation (see, for example, Keeney and Raiffa, 1976):

$$C = \sum_1^i W_i U_i$$

Each consequence value is the summation of the weights (W) multiplied by the disutilities of each consequent outcome of an attack (U). Note that we have assumed utility independence across the attributes here. Other forms of the utility function are available if this assumption is not valid.

### **3.1.3 Vulnerability determination**

An Army risk assessor will conduct a site inspection to determine the vulnerability for each WDS component. The vulnerability score represents the risk assessor's probability assessment of attacker success which range from 0 to 1 as shown in Table 3. The vulnerability criteria description is purposely left vague and should be not discussed in open literature due to security concerns. Nevertheless, detailed descriptions are need for consistent vulnerability assessment. As a recommendation, the WSVA program could use a security checklist to score each component site in order to avoid assessor subjectivity.

**Table 3. Constructed Scale for Vulnerability**

<b>Score</b>	<b>Description</b>
<b>0</b>	Existing control measures impossible to overcome
<b>0.2</b>	Existing control measures difficult to overcome
<b>0.4</b>	Existing control measures remotely possible to overcome
<b>0.6</b>	Existing measures inadequate
<b>0.8</b>	Minimal protective measures in place
<b>1</b>	No existing safeguards

Similar to the calculation of the consequence score, the vulnerability (V) value is the summation of the weights (W) multiplied by each vulnerability (v) score to contamination, physical destruction and cyber attack.

$$V = \sum_1^i W_i v_i$$

### 3.2 Quantification of Risk

As an example of the process, I acted as the risk assessor and compiled a list of adverse scenarios for Blue Zone and evaluated risk based on the methodology described in the previous section. Recall from an earlier section that the Threat value used for Blue Zone is 0.70. Table 4 provides a list of consequence values based the decision maker disutility preference. However, these values are subjective until hydraulic modeling can verify the outcome for each scenario. The vulnerability values provided for each scenario are assigned base on the WDS component's resistance to contamination, physical destruction and cyber. The results are shown in Table 4. The initial assessment finds that the risk of physical destruction and cyber attack to key military WDS components is negligible, which reflects the historical data on WDS attacks (USACHPPM TG 188, 2008). This of course could change in the future due to adversary adaptation, but for the present example cyber attack and physical destruction of components will not be considered further.



Contamination of Water Tower 1 and Water Tank 2 had risk scores of 0.14 and 0.04 respectively. These risk scores reflect the situation at the moment of the assessment and can change as either one of the three risk components changes. Scenario 1's score of 0.14 does not mean the scenario is 14 times more likely to occur than scenario 7 with a score of 0.01. Rather, the scores reflect that the outcome of scenario 1 is 14 times more risky relative than scenario 7. Although not every scenario needs hydraulic modeling, the assessor should verify those scenarios with the highest risks. To demonstrate the practical use of hydraulic, contaminant fate and transport modeling, the paper will model the contamination of Water Tower 1(Scenario 1), which also had the highest risk score.

**Table 4. Risk Table**

Scenarios	Type of Attack	Components	T	C	V	Risk
1	Contamination	Water Tower #1	0.70	0.50	0.40	0.14
2	Contamination	Water Tank #2	0.70	0.50	0.10	0.04
3	Contamination	Primary Pump	0.70	0.20	0.00	0.00
4	Contamination	Hexagon Pump	0.70	0.08	0.00	0.00
5	Contamination	Pipe 163	0.70	0.58	0.00	0.00
6	Physical Destruction	Water Tower #1	0.70	0.06	0.11	0.00
7	Physical Destruction	Water Tank #2	0.70	0.15	0.11	0.01
8	Physical Destruction	Primary Pump	0.70	0.21	0.11	0.02
9	Physical Destruction	Hexagon Pump	0.70	0.01	0.04	0.00
10	Physical Destruction	Pipe 163	0.70	0.01	0.14	0.00
11	Cyber Attack	Water Tower #1	0.70	0.00	0.03	0.00
12	Cyber Attack	Water Tank #2	0.70	0.00	0.03	0.00
13	Cyber Attack	Primary Pump	0.70	0.00	0.03	0.00
14	Cyber Attack	Hexagon Pump	0.70	0.00	0.00	0.00
15	Cyber Attack	Pipe 163	0.70	0.00	0.00	0.00

### 3.3 Simulation

*“The sheer size of drinking water sources and distribution systems (both in terms of water volume and detention time) and the presence of existing treatment processes significantly reduce the effectiveness of such an attack on a water source or treatment plant. Intentional contamination of*

*a raw water supply using a known or potential biological warfare agent, for example, would require at least 30,000 times the toxic dose for each individual placed at risk, even neglecting natural attenuation and ordinary treatment efficacy. This is not an effective point to contaminate the supply unless massive amounts of contaminant are applied. This type of attack, in order to be effective, would likely be aimed at a storage tank or a part of the distribution system serving a specific high-profile building” (USACHPPM TG 188, 2008).*

Serious attackers would recognize that water dilution is a major obstacle in a contamination attack. Out of the dozens of possible injection point in the WDS, Water Tower 1 is selected as the most likely contamination location. The intended target of the attack is the Hexagon building. Scenario 1 consists of an unknown quantity of one or more contaminants released into Water Tower 1 at 12:00 a.m. The hydraulic and water quality simulation of the WDS was modeled using EPANet 2.0 for duration of 168 hours (1 week). This duration corresponds to the 7 day MEG. Recall that people who consumed water from a contaminated node are counted as population exposed to the contaminant. The goal of hydraulic modeling of a contaminant is to assess how the contamination spreads (Torres et al., 2009). Therefore, this paper will not speculate on the short and long term adverse health effects of unknown contaminants. Nevertheless, when consumption of the contaminant is greater than the 7 day MEG for 7 days, there is cause for health concerns.

### **3.4 Uncertainties in model inputs**

In the base scenario, an unknown contaminant was released into the water tower. Some assumptions about the WDS characteristics were made, such as instantaneous mixing. Three important unknown inputs of the model are 1) type of contaminant used (based on MEG), 2) reaction rate of the contaminant and 3) quantity of the contaminant. These uncertainties in the

model input will propagate to uncertainties in the model output. Monte Carlo simulations, a technique based on repeated random samplings is used to obtain the distribution of an unknown probabilistic function ([http://en.wikipedia.org/wiki/Monte\\_Carlo\\_method](http://en.wikipedia.org/wiki/Monte_Carlo_method)). In order to quantify the uncertainties in the model output, 2500 contamination simulations of scenario 1 were conducted using MATLAB 2013a.

The three uncertainty parameters of the model are displayed in Table 5. The toxicity of the contaminant is judged on the basis of the MEG and was modeled as a Lognormal (-0.0146, 2.816) distribution generated from 167 known 7-Day Negligible MEG from USAPHC Technical Guide 230 (2010). Each simulation randomly generates a contaminant toxicity based on this distribution. Since the contaminant used in the attack is unknown, its aquatic characteristics are also unknown. A normal (-0.5, 0.25) distribution curve is used to generate the reaction rate of the contaminant for each simulation. The benefit of using random reaction rates is that it could represent the synergetic effort of two or more contaminants. The contaminant quantity is generated from a lognormal (-0.168, 0.642) distribution from Torres et al. based on a mass of 93.75 kg (Torres, 2009).

**Table 5. Uncertainty Distribution**

Input	Distribution	Mean	Standard deviation	Notes
MEG	Lognormal	-0.0146	2.816	Closely matches U.S. Army data on known contaminant MEGs
Reaction Rate	Normal	-0.5	0.25	Simulates chemical reaction speed in water
Quantity	Lognormal	-0.168	0.642	Represents a contaminant base mass of 93.75 kg

The hydraulic models are able to verify the potential danger of a contamination attack on Water Tower 1. As a result, the assessor could use the hydraulic data as evidence to recommend countermeasures to lower the Risk Score for scenario 1. Monte Carlo simulations were conducted in MATLAB 2013a and the results of the histogram are shown in Figure 5. In 1,176 of

the simulations (47%), people were not exposed above the MEG level. The mode from the Monte Carlo simulations is 0 EI while the median was 230 EI. One can speculate that a random, unplanned attack using common contaminants in reasonably large quantities may not expose consumers above the 7 day negligible MEG. However, nearly 53% of the contamination simulations were over the MEG level ranging from 230 to 405,503 EI. The expected outcome is 53,126 EI, a figure not to be taken lightly for decision makers.

A percentile graph derived from the Monte Carlo simulations show the variability in population exposure (Figure 6). The results show that contaminant uncertainties in model inputs produced high variability in exposure levels. Also, the exposure occurs during the daytime hours between 7:00AM and 8:00PM each day which corresponded to the period of highest water demand.

Understandably, exposure decreases to near zero when people leave their work at night. In most simulations, EI decreased each day due to contaminant decay over time. Near the 50th percentile, the population of Hexagon is barely exposed to contaminant concentrations above the MEG. At the 75 percentile, the EIs spike initially but decay to almost zero after four days. In the worst contamination simulation given the distributions, an estimated 9,000 EIs occurred daily without any abatement. Recall that 6,900 people work in the Hexagon building. A dangerous contaminant could conceivably cause significant illness for the exposed population, which represents 58% (4,000) of Hexagon employees. One hidden aspect of only accounting for above MEG exposure is that a widespread contaminant in the WDS may cause more exposure but less health impact due to dilution.

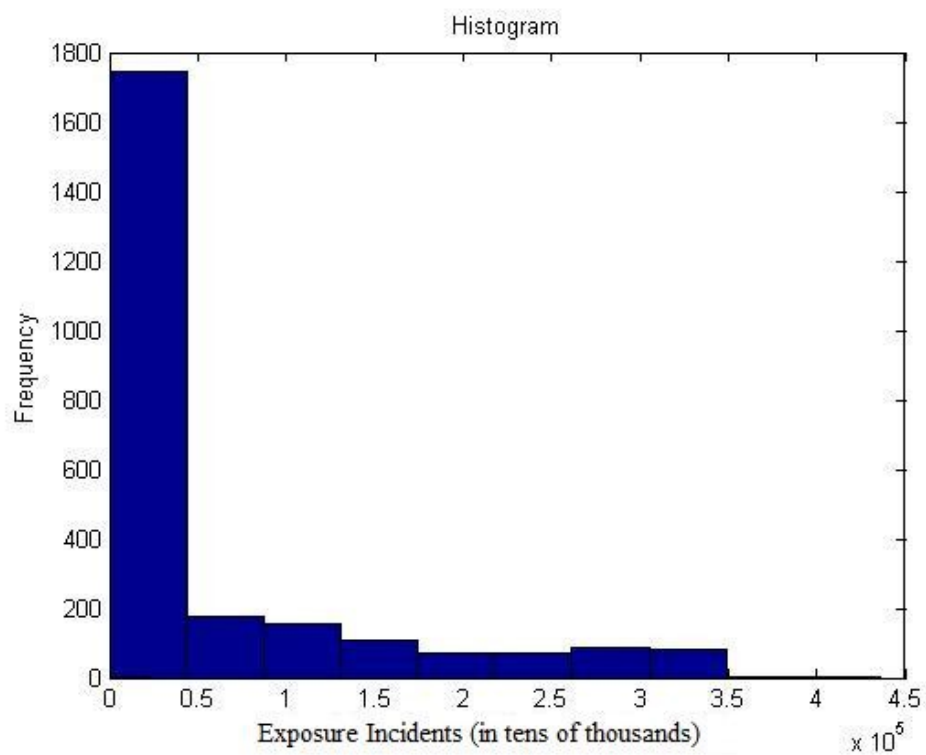


Figure 5. Histogram for 2500 Simulations

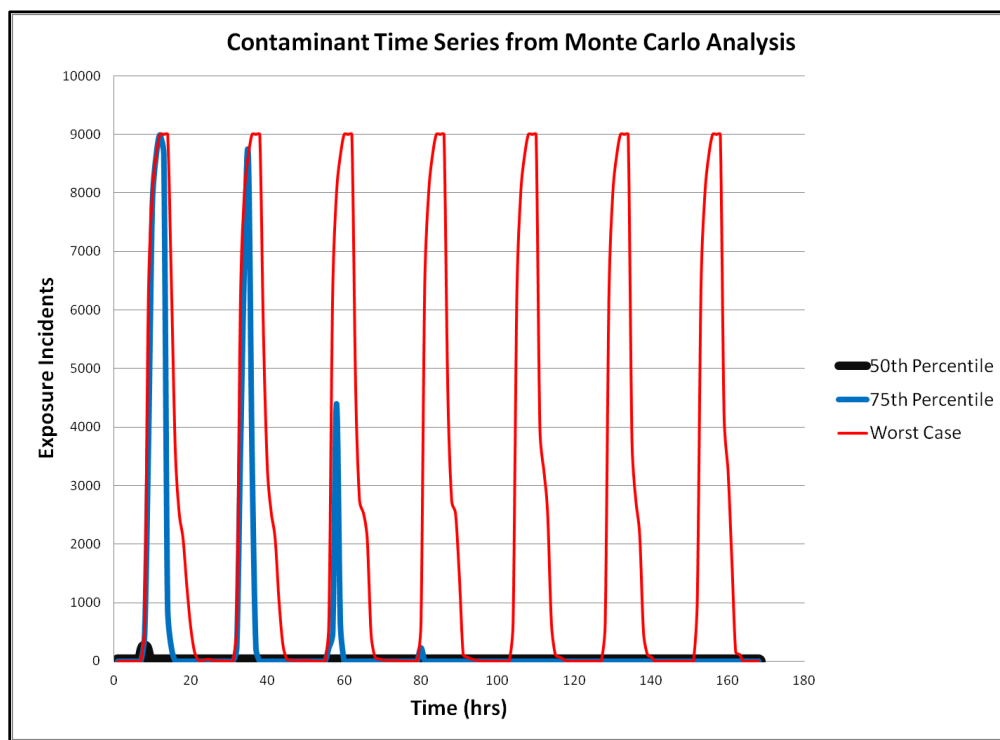


Figure 6. Time Series Exposure from MC Simulations

The results from Monte Carlo simulations provided a range of possible outcomes given many stochastic input variables. In order for the predicted outcome to be accurate, it helps that contaminant characteristics are known. Attackers have an advantage in terms of information because of the asymmetric nature of the conflict (Brown et al., 2012). Public web sites offer useful infrastructure information that could be used by terrorists to conduct their own hydraulic modeling. The Al Qaeda training manual states that it is possible to gather at least 80% of enemy information from public sources (Federation of American Scientists, 2006). If our adversaries can obtain infrastructure blue print and consumption data through public means, they would likely have enough information to build somewhat accurate hydraulic models for U.S. military installations. Combined with the knowledge of the contaminant characteristics, our adversaries can optimize contamination methods to strike against the U.S. military WDS. It is ironic then that this tool may better support the attackers, who can decide the type of chemicals used, where to contaminate, how much contaminant to use, and the time. Therefore, it is imperative that military installations protect their public data.

### **3.5 Evaluation of a Catastrophic Scenario**

Due to the enormous stakes involved in military operation, decision makers always want to know the worst case scenario. However, the “worst case” scenario is rarely predictable despite however improbable it may seem. Instead, the assessor can present the worst outcome from the simulations to the decision maker as a possible catastrophic scenario. The most catastrophic outcome generated from the 2500 simulations of Scenario 1 had a contaminant concentration of 6.175 mg/L (41 kg), reaction rate of 0.067 and MEG of 0.0003 mg/L, rendering the contaminant

extremely toxic. Unlike the vast majority of the generated contaminants, this contaminant multiplied in the water supply, which mimics a biological microorganism.

In order to visualize how contaminants propagation throughout the Hexagon Building, a Day 1 timeline is created with commentary below (Figure 7). The eight hour time series is advanced in increments of two hours to demonstrate how office hour demand can affect the hydraulic characteristics of the WDS.

**7:00 AM:** 632 EI have occurred in the Hexagon building. The sudden demand increase caused water to flow from Water Tower 1 into the WDS. Prior to this time, water from the water treatment plants were sufficient to meet the overnight usage.

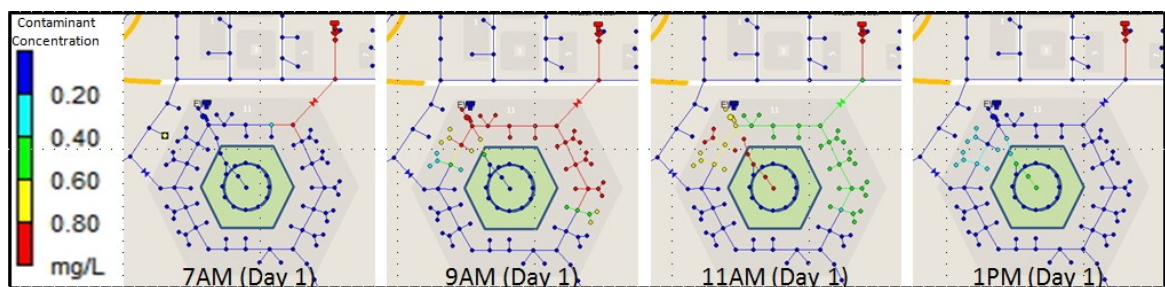
**9:00 AM:** 14,908 EI have occurred in the Hexagon building in two hours. The contaminant had spread to the northern half the Hexagon's point of consumption nodes. It is also when the contamination is at its highest concentration peak.

**11:00 AM:** 32,545 EI have occurred in the Hexagon building in four hours. The contaminant concentration in the Hexagon pipelines has decreased overall from two hours ago. However, more exposure incidents are occurring due to lunch time activities. Notice in the center of the Hexagon plaza, the Hexagon café node is active causing many more EI.

**01:00PM:** 50,539 EI have occurred in the Hexagon since 7:00AM. Water demand usages decrease such that the hydraulic characteristics in the Hexagon building had reverted back to the low demand pattern. Water in the north half of the Hexagon building is now flowing from the water treatment plants once again instead of the contaminated water tower. However, there are

still remnants of contaminated water left in a portion of the Hexagon building that continued to cause exposure.

In our catastrophic simulation of Scenario 1, over 400,000 EI occurred in 168 hours. Each day, the rise and fall of the number of EI is closely correlated to the actual water demand. Although it is difficult to predict the final health impact from the contamination attack, the contaminant's potential danger may be inferred from known databases. Our unknown contaminant was compared to a list of known cytotoxicity, or toxins harmful to cells. Out of this list of 347 toxins ([http://ntp.niehs.nih.gov/iccvam/docs/acutetox\\_docs/guidance0801/appa.pdf](http://ntp.niehs.nih.gov/iccvam/docs/acutetox_docs/guidance0801/appa.pdf)), only two had a LD50 concentration less than our initial contaminant concentration in Water Tower 1. Assuming the worst, suppose that the contaminant dumped into the Water Tower is one of these two extremely dangerous toxins. From our comparative speculation, people who were exposed to multiple EI are at serious health risk and the attack would cripple the Hexagon military operations.



**Figure 7. Contaminant Propagation**

### 3.6 Sensitivity Analysis

A sensitivity analysis is conducted on the model output of Scenario 1-catastrophic simulation.

Each of the three input factors (type of contaminant used, reaction rate of the contaminant and



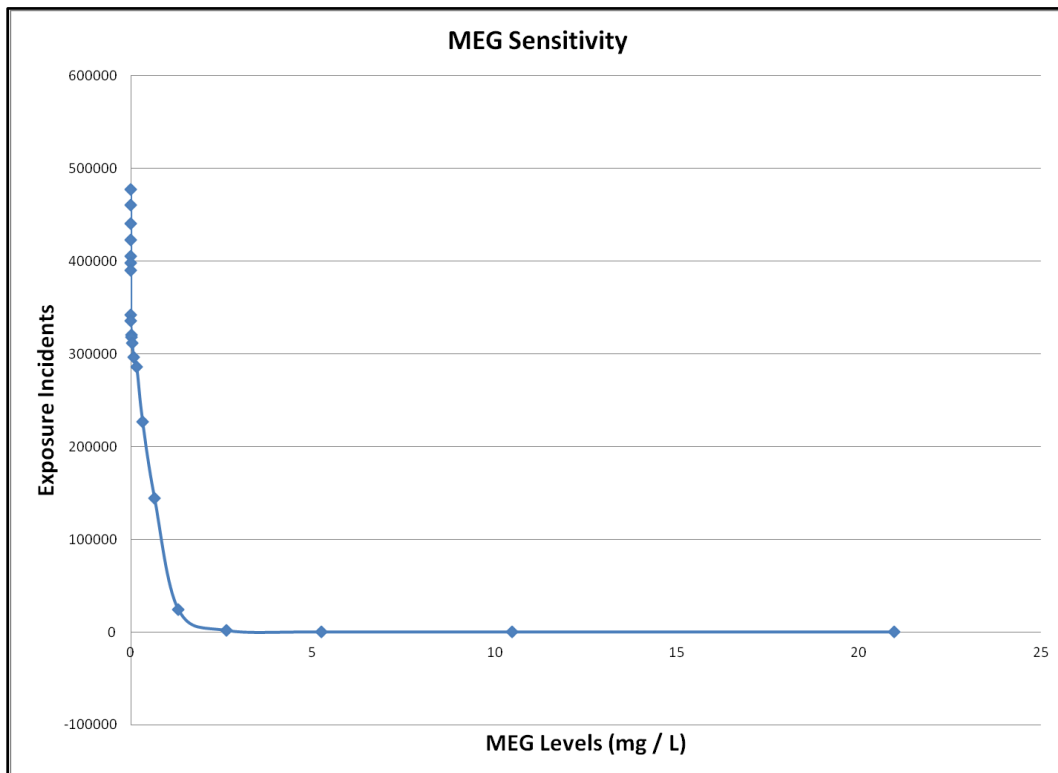
quantity of the contaminant) is isolated and evaluated while the other two remain at their initial value (catastrophic simulation). The input for contaminant used and contaminant quantity are incrementally increased from 0 mg/L to measure the corresponding EI output. In the case of reaction rate, the values range from -10 to +10 to produce the EI reactions.

The number of EI is extremely sensitive to the toxicity of the contaminant (Figure 8a). Recall that the toxicity is judged by the contaminant's MEG values, comparable to EPA's MCL values. As the MEG drops from 5.24 mg/L to 0 mg/L, exposure incidents quickly jump to the maximum number of EI possible for the Hexagon Building, estimated at 477,052 over 168 hours.

The reaction rate of the contaminant has the least influence over the number of EI (Figure 8b). Chemical contaminants will have a decay or growth rate. Unfortunately, EPANet 2.0 does not model the propagation of biological contaminants. Therefore, the use of a biological contaminant will provide more uncertainty than chemical contaminants.

The number of EI is not particularly sensitive to the quantity of the substance used in the attack (Figure 8c). A minimum quantity of 1.67 kg of the unknown contaminant is required in the attack on Water Tower 1 in order to trigger exposure above the MEG threshold in the Hexagon Building. At the MEG threshold, the contaminant quantity would cause 350,000 EI. Further increases in the quantity would only result in marginal increases in EI. It takes significantly more contaminant quantity to eventually reach the maximum exposure incident. However, increased contaminant quantity will also increase contaminant concentration. Although EI responded marginally to the increases in contaminant quantity, the dose-response curve of the exposed population would likely be much more sensitive to the increase in contaminant concentration. The contaminant quantity is significant because an increase in concentration will increase toxicity health risks among the exposed population.

The model output (EI) is significantly sensitive to two of the three input factors (toxicity and reaction rate) in our scenario modeling. Significant EI uncertainty exist in the number of EI because assumptions are made to represent strong simplifications, relevant data is not available, and there is lack of agreement among experts (Flage, 2009). As a result, small changes in our input will result in large changes in our output.



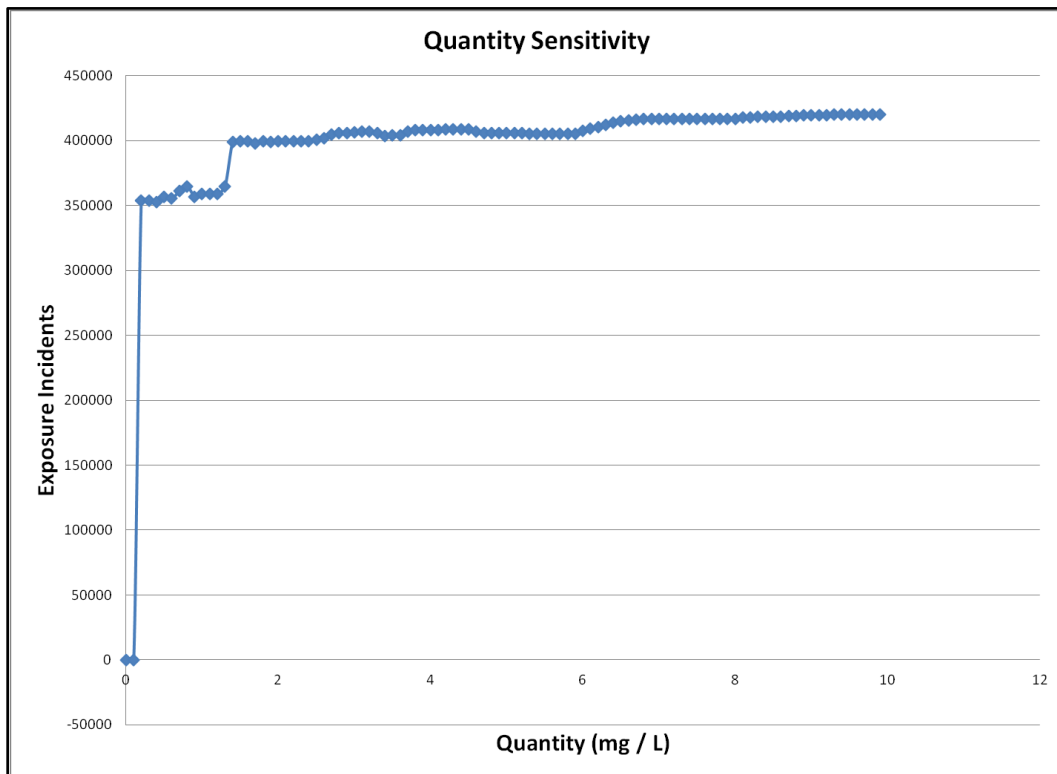
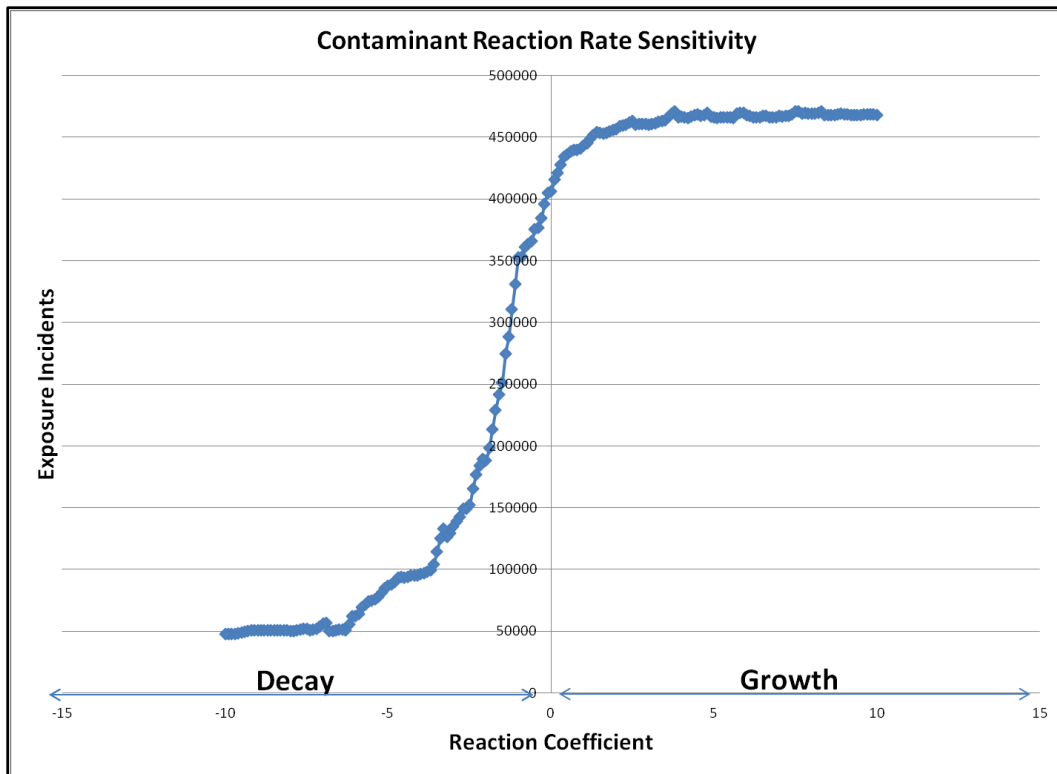
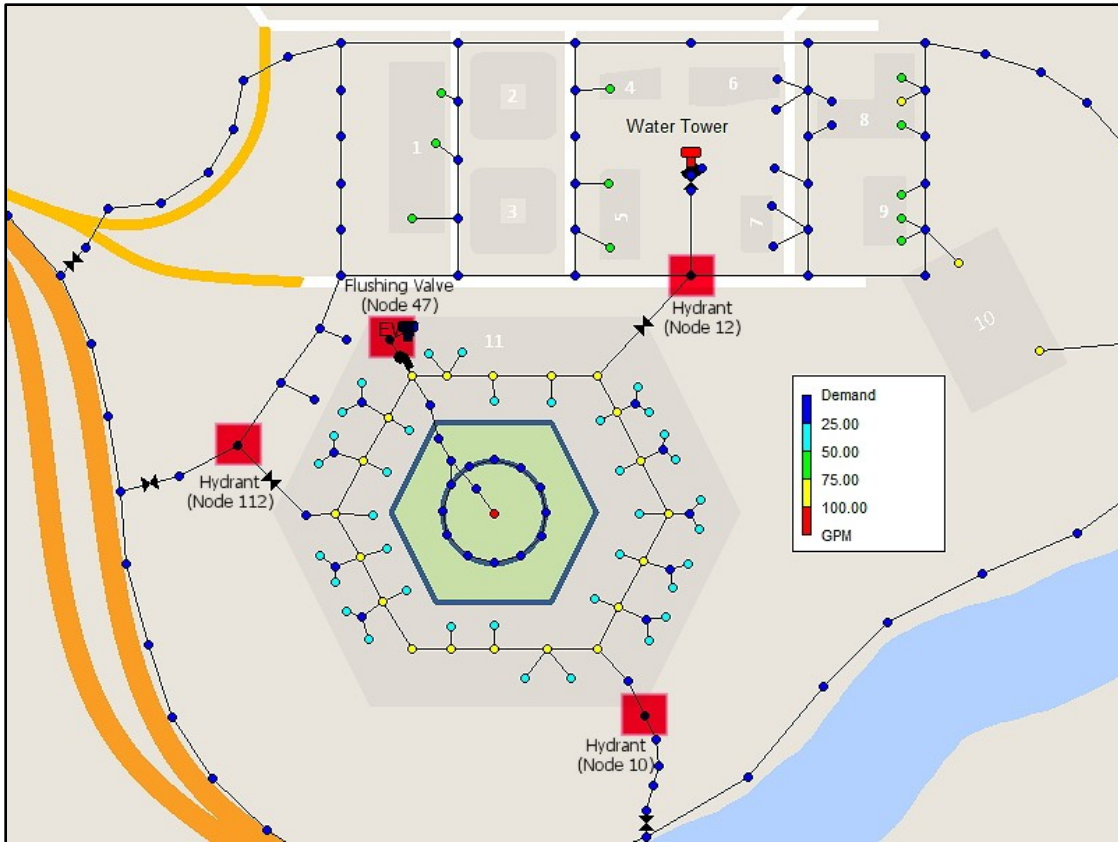


Figure 8. Sensitivity Analysis of (a) MEG Sensitivity, (b) Contaminant Reaction Rate Sensitivity, (c) Quantity Sensitivity.

### **3.7 Emergency Response Plan Evaluation**

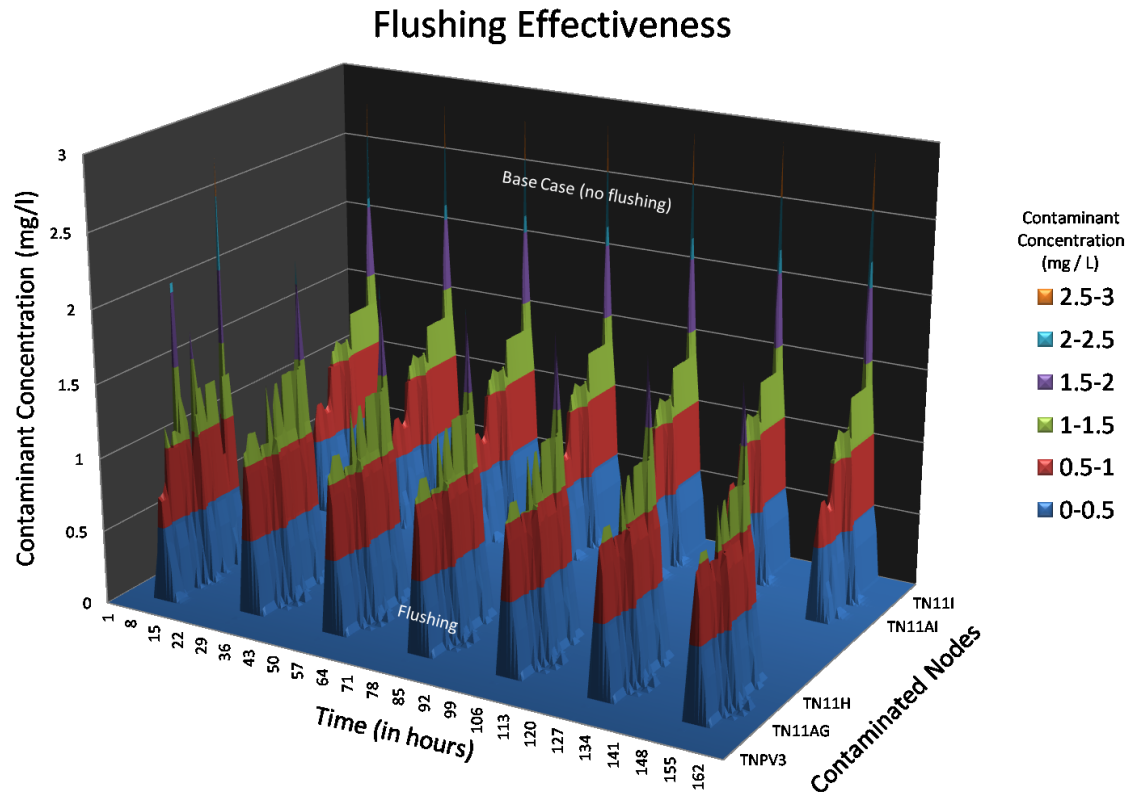
Hydraulic, contaminant fate and transport modeling are used to evaluate Blue Zone's ERP in the added step of the WSVA2 methodology. It is probable that a determined, competent person could carry out a successful contamination attack on the military WDS despite countermeasures. Therefore, it is important to determine whether the current ERP can sufficiently mitigate the contamination threat.

An attack response scenario is generated based on known mitigation practices and existing research. The timeline of events are arbitrary. In our attack response scenario, the water quality monitors notified the Department of Public Works (DPW) that water quality in the Hexagon has dropped below acceptable levels. In accordance with the ERP in a high threat region, DPW started flushing water out from preselected fire hydrants (node 12, 112, 10) and from the Hexagon emergency water tank (node 47) as shown in Figure 9.



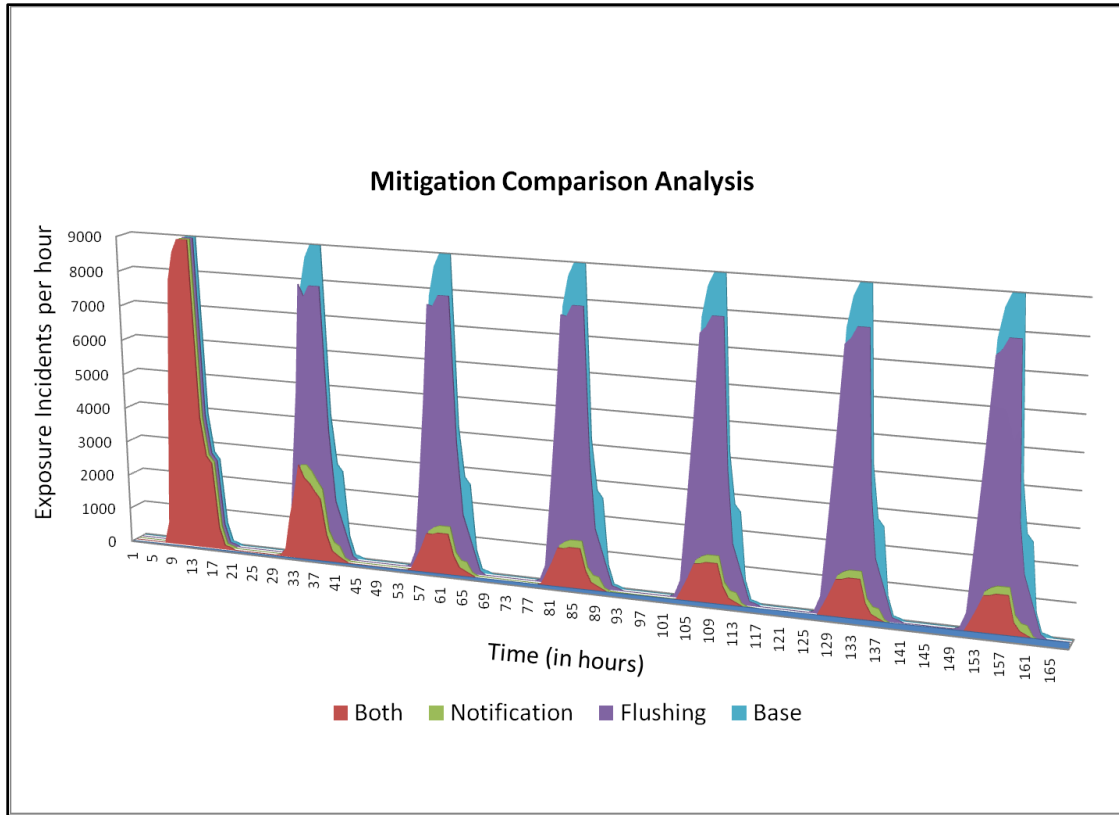
**Figure 9. Flushing Nodes**

At 7PM on Day 1 ( $t = 19$  hours), these nodes were opened to flush out the contaminants in the WDS. The combined flow rates at the flushing nodes are 2,000 GPM. The plan required continuously flushing until the water quality is under the MEG. The results of this mitigation are compared against taking no action for the Scenario 1 in Figure 10. In this scenario, flushing efforts managed to noticeably reduce the concentration at all the contaminated nodes in the WDS. Nevertheless, the response failed to bring the level below the MEG over time. Flushing the predestinated hydrants in the ERP are not effective. This paper did not attempt to optimize flushing effectiveness by testing the entire range of possible hydrant combinations, but it is likely that a different set of hydrants is more effective than the current ERP hydrants.



**Figure 10. Flushing Effectiveness**

The second mitigation strategy involves notifying all personnel to stop consuming water in a manner that would cause exposure. After some investigation and water testing, DPW decided that Water Tower 1 was infiltrated and likely contaminated by hostile groups or individuals. Unfortunately, the water quality notification was not distributed to the general public until 1:00 AM on day 2. People notified each other through direct communication, social media, and word of mouth. From 1AM (day2) to 7PM (day2), 10% of the unnotified population was alerted and chose to stop tap water consumption each hour and switched to bottled water. The notification compliance rate ranged from 42% to 84% in a number of historical studies (Zechman, 2011). In our scenario, 85% of the largely military population complied with the notification by 7PM on day 2.



**Figure 11. Mitigation Comparison Analysis**

The results show that a dramatic reduction in military water consumption led to a significant decrease in EI. In comparison, the attempt to flush out the contaminant only had some success in lowering EI (Figure 11). Applying the combined strategy of notification and flushing is only marginally better than the notification mitigation.

## **4. Conclusions and Future Work**

### **4.1 Conclusions**

A quantifiable approach to military WSVA offer decision makers the ability to make better informed decisions. The use of hydraulic models is able to verify the potential dangerous scenario conceived by risk assessor. 53,126 EI resulted from the contamination attack on Water Tower 1. The analysis also speculated on the results of the most catastrophic simulation given the contaminant's input parameters. Over 400,000 EI occurred in 1 week which affected over 4,000 people in the Hexagon Building. As a result, people who were exposed to multiple EI are at serious health risk and the attack would have likely cripple the Hexagon's military operations indefinitely. The model output (EI) is significantly sensitive to two of the three input factors (toxicity and reaction rate) in our scenario modeling. As a result, small changes in our input will result in large changes in our output. In a catastrophic scenario, the current ERP can not sufficiently mitigate the contamination threat below MEG level. The flushing strategy from the pre-designated hydrants is only somewhat effective in lower the contaminant concentration but the notification strategy resulted in significant decreases in EI over time. Unfortunately, the combined strategy of notification and flushing is not enough flush out the contaminant over time.

### **4.2 Future Work**

Current military budget realities may reduce the WSVA program altogether if it is not effective. Realistically, the local military installation Anti-Terrorism office can conduct all the aspects of the WSVA without a dedicated team of risk assessors. However, the local AT offices still need to verify their own findings with the WSVA assessors at U.S. Army Public Health Command (USAPHC). USAPHC could complete the added steps of WSVA2 to supplement the on site



assessment with the provided information. A cost benefit analysis on a pilot WSVA2 program may help the WSVA program to evolve over time.

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## Resume

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### **EDUCATION**

**Johns Hopkins University**, Baltimore, MD **2012 – 2014**  
M.S.E. in Environmental Engineering

**Texas A & M Health Science Center**, College Station, TX **2010**  
12 graduate credits (4.0 GPA)

**United States Military Academy**, West Point, NY **2001 – 2005**  
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**New Mexico Military Institute**, Roswell, NM **2000 – 2001**  
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### **RESEARCH EXPERIENCE**

**Independent Study     Johns Hopkins University     2013 – 2014**

- Finished an independent study focused on the improvement of the water system vulnerability assessment of military water distribution system using hydraulic modeling and quantitative risk analysis

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**Armor Officer**, United States Army **2005 – 2009**  
**Environmental Engineering Officer**, United States Army **2009 – 2012**

**Projects Officer     U.S. Army Public Health Command Region - North     2010 – 2012**

- Deputy Chief of the Environmental Health Engineering Division and responsible for the environmental programs management of nine officers and two civilians within a 20-state area of operation.
- Environmental health projects officer with duties to provide technical services and consultation in the areas of water systems vulnerability, drinking water supply, regulated medical and hazardous waste management.

- Assumed an information technology project to maximize the efficiency of the command oversight.

**Commander                      A Company, U.S Army Medical Department Activities      2008 – 2009**

- Commander of the high profile Warrior Transition Unit and directly responsible for the welfare, training, and combat readiness of 60 wounded warriors, 24 medical and administrative staff and their families.
- Refined the Triad of Care program to streamline the transition process for wounded warriors which led to zero suicidal, accidental or medical deaths in the Fort Irwin WTU since its conception.
- Established training programs for transitioning Soldiers and provide comprehensive information on the transition process and support systems in order to create seamless transition for 215 wounded warriors.

**Executive Officer              A Company, U.S Army Medical Department Activities      2007 – 2008**

- Selected by the installation chief of staff for the high-visibility position as the first executive officer of the Fort Irwin and Naval Medical Center San Diego Warrior Transition Units.
- Responsible for medical treatment, training, morale, professional development, health, and welfare of over 200 wounded warriors, 18 administrative and medical staff and their families.
- Created training programs, comprehensive information on the transition process, support systems, address and resolve concerns and complaints for wounded warriors and ensure a high quality of care.

**Executive Officer              E Troop, 2-11th Armored Cavalry Regiment                                      2007**

- Executive Officer and second-in-command for an Infantry Troop (over 108 Soldiers) in an Armored Cavalry Squadron with the dual mission of combat deployment and training deploying units at the National Training Center.
- Responsible for the logistics, administration, and maintenance to support the unit including over 40 combat vehicles and equipment worth in excess of 50 million dollars.
- Planned coordination for simulated insurgency and combat at the National Training Center to provide realistic training to four Brigade Combat Teams numbering tens of thousands of U.S. and allied forces.

**Platoon Leader                      G Troop, 2-11th Armored Cavalry Regiment                                      2006 – 2007**

- Tank Platoon Leader for a Heavy Tank Platoon in an Armored Cavalry Squadron with the dual mission of combat deployment and training deploying units at the National Training Center.

- Responsible for the safety, morale, training, mission accomplishment and accountability of 15 Soldiers, nine vehicles and ancillary equipment worth in excess of 14 million dollars.
- Planned and organized insurgency operations at the National Training Center to provide realistic training to over ten Brigade Combat Teams numbering over fifty thousand U.S. and allied forces.

### **MILITARY EDUCATION**

- Medical Service Corps Captain's Career Course, 2011
- Military Preventive Medicine Course, 2010
- Army Scout Platoon Leaders Course, 2005
- Army Armor Basic Officers Course, 2005
- Army Air Assault School, 2003

### **CERTIFICATIONS**

- Fundamental Engineering Exam – New York
- Defense Language Proficiency-Mandarin
- Advance Medical Waste Treatment
- Cross Connection Controls (Surveyor)
- Operational Risk Management for Deployment
- Occupational & Environmental Health Surveillance